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# The Role of Material/Energy Resources and Dematerialisation in Economic Growth Theories

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**Abstract**
The nature of energy and material resources in an endogenous growth theory framework is clarified. This involves three modifications of the conventional theory. Firstly, multiple feedback mechanisms or "growth engines" are identified. Secondly, a production function distinguishes between resource use, technical efficiency and value creation. Thirdly, the impact of the cost of production through demand on growth is accounted for. A formal model is analytically solved under a condition of a constant growth rate. Given model complexity, numerical experiments are performed as well, providing relevant insights to the academic and political debates on 'environmental Kuznets curves' and 'dematerialization'.

**Keywords:** dematerialization, environmental Kuznets curve, feedback mechanisms, production function specification, resource scarcity, value creation

**JEL classification:** O11, O33, O41, Q32, Q43

# 1. Introduction

That the scarcity of natural resources and environmental pollution, as well as policy goals like recycling of materials, dematerialization, and increasing energy efficiency, impose certain constraints on economic activity is indisputable. The nature of those constraints as applied to economic growth are both subtle and contentious, and have been insufficiently addressed in applications of standard growth theory to environmental resources [Beltratti, 1996; Chichilnisky et al. 1997; Dasgupta and Heal 1979; Pezzey, 1989; Toman et al. 1995]. A new approach to growth theory involves at least two modifications of the conventional theory. First, to explain endogenous growth it must reflect the existence of self-reinforcing feedback mechanisms or "growth engines" apart from population growth and the traditional savings-investment-capital accumulation mechanism. The knowledge-accumulation mechanism proposed by various versions of endogenous growth theory is one candidate, but not the only one. The role of learning and `experience', as well as the role of declining natural resource (notably fossil fuel) prices, as drivers of past and present economic growth, need to receive attention in formal models of economic growth.

Second, a modified growth theory should explicitly reflect the fact that important (i.e. scarce) factors of production in economics can and do change over time. When non-renewable natural resources were perceived as available without limit, i.e. not scarce, they could be regarded as intermediate products of scarce labor and scarce produced capital. However, in the future, as growth continues, both renewable and non-renewable natural resources may be scarce and limiting, and increasingly so, whereas unskilled human labor and produced capital will be plentiful, also increasingly so.

These ideas will be elaborated in a formal model that includes two major innovations relative to existing growth models. A general production function distinguishes between resource use, technical efficiency and value creation. In addition, the impact of cost of production on demand and in turn on growth is included. The production and demand submodels render separate insights. As the combination of the two leads to a complicated model this will be solved under an extra condition, namely that the growth rate is constant. It will be argued that the resultant model is capable of generating new insights about questions regarding limits to growth, sustainable development, "Environmental Kuznets Curves" and dematerialization (see van den Bergh and Hofkes 1998). Note that the model presented here adopts an entirely different approach than the standard literature on extensions of (exogenous or endogenous) growth theory with (renewable or nonrenewable) natural resources or environmental pollution (see Dasgupta and Heal 1979; Smulders 1999).

The organization of this paper is as follows. Section 2 briefly discusses Neoclassical growth theory from theoretical and empirical perspectives. Section 3 presents an alternative view on growth, by distinguishing three growth mechanisms. Section 4 presents a related alternative view and formalization of the aggregate production function. Section 5 provides a formalization of the three growth mechanisms. Section 6 extends the model with demand side factors. Section 7 presents analytical results. Section 8 shows some numerical results. Section 9 concludes.

## 2. Neoclassical Growth Theory

The neoclassical one-sector growth model has three crucial predictions. The first one is that the contribution of capital investment to growth will slowly and finally cease due to saturation, i.e. diminishing returns to man-made capital. A second implication follows is that the *only* source of growth thereafter must be technological progress, which the model does not explain and treats as exogenous. Usually this is done by introducing a simple exponential function of time, thus representing technical progress as an automatic and gradual process. The third prediction is that poorer countries will grow faster than rich ones, other factors remaining the same. Thus, economic convergence should occur.

It is well-known that the three key predictions of the standard theory are not consistent with observation. In the first place, there is no indication of approaching capital saturation. In the second place, the 16 richest countries grew much faster in the 1950–1970 period (3.7% per annum) than they did in the prior 80 years, when growth averaged about 1.3% per annum. Even after the observed slowdown in the early 1970s, growth continued at around 2.1% per annum which is slower than 1950–1970, but faster than the long-term average. In the third place, a simple scatter chart of growth rates vs. GDP for 118 countries, shows no detectable correlation between the two variables, even though the standard theory implies that countries with higher GDP should have lower growth rates [Barro and Sala-i-Martin 1995]. On the other hand, until 1997 the "tiger" economies of East Asia were undoubtedly growing faster than the more industrialized countries. This suggests that other factors account for low growth rates elsewhere.

These facts have motivated a recent flurry of interest in revising the neoclassical theory to endogenize technological progress, without giving up the growth-in-equilibrium assumption — and associated with it the assumption of rational behaviour of economic agents. The resulting so-called 'new' theory of endogenous growth has uncovered several alternative (and possibly more realistic) ways of accommodating the 'stylized facts'of growth [Romer 1994]. These stylized facts are as follows : (1) market systems involve many firms; (2) discoveries are public knowledge (non-rival goods); (3) physical activities are replicable, whence the aggregate production function must be homogeneous of degree one in all inputs that can be owned and exchanged (i.e. they are rival goods); (4) technological progress is a consequence of human activity; (5) competition is imperfect. This theory was kicked off by Paul Romer, who simply discarded the neoclassical condition of diminishing returns to capital and defended that step by arguing for increasing returns to human capital, thanks to positive spillovers [Romer 1986]. He further showed that, contrary to earlier opinion, such models could be robust.

Since then models have been constructed models of sustained growth with imperfect competition, trade, vertical innovation, environment, etc. [Lucas 1988; Romer 1987, 1990; Jones & Manuelli 1990; Rebelo 1991; Grossman & Helpman 1991; Aghion and Howitt 1992; Smulders 1994, 1999]. In many of these models the production function takes the Harrod-Domar form

$$Y = A\,K \tag{1}$$

where $A$ is a constant and $K$ stands for 'knowledge capital' or some combination of physical and reproducible factor inputs. All of these models assume that investment in knowledge or technology yields increasing returns, offsetting the diminishing returns to physical capital, allowing constant returns to scale at the economy-wide level. Thus, in the basic AK model the long-run growth rate of capital and output depends only on the growth of knowledge. If the capital (knowledge) stock is governed by the usual relationship between investment/savings rate $s$ and depreciation rate $\boldsymbol{d}$, i.e.

$$\dot{K} = s\,Y - \boldsymbol{d}\;K \tag{2}$$

then it follows that the growth rate $r$ is given by

$$r = \dot{Y}/Y = \frac{\mathrm{d}Y}{\mathrm{d}K}\dot{K}/Y = \frac{\dot{K}}{K} = sA - \boldsymbol{d} \tag{3}$$

This implies that under endogenous growth the long run growth rate can be constant and positive as long as the technological parameter $A$ is larger than the depreciation-rate/savings-rate ratio.

It must be said, however, that notwithstanding its ingenuity, all of the above-cited work involves a certain 'sleight-of hand' insofar as it depends on just one fundamental change in the standard menu of assumptions. It exploits the 'public goods' attribute of knowledge to achieve increasing returns to capital (including human capital). The other relaxations to the standard theory, such as imperfect competition (and incomplete appropriability of intellectual capital) had already been made.

There are some limitations of this framework. First, most discoveries are not instant public knowledge. This is even true of published discoveries in physics or chemistry, not to mention other kinds of knowledge that contribute fundamentally to productivity. Moreover, assuming that firms always act rationally is equally unrealistic. Neo-Schumpeterian theories have emphasized bounded rationality and stochastic processes, which cause persistent economic disequilibria (Nelson and Winter 1982; Dosi *et al.* 1988). In contrast to this is the younger research program that aims to combine endogenous growth theory, based on deterministic rational behaviour, with Schumpeterian "creative destruction", also referred to as "vertical innovation" (Aghion and Howitt 1998). This approach remains in the tradition of equilibrium growth theory. Either approach still has to prove its empirical value.

An important question arises, namely: is it possible to achieve perpetual exponential growth with a constant savings rate (non-increasing investment) and declining resource inputs? This is a question that has been addressed before, of course, in connection with the "limits to growth" debate of the early 1970s. But the mainstream economists' response then was mainly based on analysis with simple abstract neoclassical (non-endogenous) growth models of the Cobb-Douglas type postulating natural resources as a substitutable input, but without any resource-related feedback mechanism [e.g. Solow 1974; Stiglitz 1974, 1979].

Given the apparent importance of material resources (and energy) in both capital and consumption goods, this assumption did not satisfy some critics of the neo-classical growth theory [e.g. Georgescu-Roegen 1979; Daly 1997]. Applications of growth models incorporating physical flows and mass balance constraints provide one alternative perspective (van den Bergh and Nijkamp 1994; Gross and Veendorp 1990).[1] The following section presents another alternative view on economic growth.

## 3. Growth Mechanisms Reconsidered

It is now generally assumed that technological progress has been, and continues to be, the major contributor to increasing the productivity of human labor. But, to gain further insight it is necessary to look more closely at the specific mechanisms. What we seek to incorporate, in particular, are three feedback mechanisms as shown in *Figure 1*.

[ Insert *Figure 1. Three growth mechanisms.* ]

*1. The "resource use" (fossil fuel) growth engine*

Economic history suggests a quite robust energy-growth feedback (EGF) relationship. This resource-driven feedback mechanism for growth is indicated by loop 1 in *Figure 1*. It can be described briefly as follows: technological progress has made fossil fuels steadily and dramatically cheaper and more convenient to use since the early eighteenth century. This, in turn, encouraged the substitution of fossil fuel-derived energy and mechanical power for work by animals and humans. It also had a powerful impact on metallurgy — especially the smelting, refining and working of iron and steel. Both cheaper fuels and better metals made it possible to construct better, cheaper and more efficient machines, including steam engines and machine tools. This, in turn, permitted continuous and drastic further reductions in the cost of mining and transporting coal (later other fuels), and the delivery of mechanical power to users, including the coal mines and the transport systems themselves. This constitutes the early form of the EGF cycle.

Conceptually the cycle consists of two separate elements. First, economic growth since 1800 has been driven to a large extent by utilizing machines (steam engines, internal combustion engines) powered by fossil fuels as a substitute for, and multiplier of, human and animal labor. Second, the extensive use of fossil fuel-derived chemical fertilizers and pesticides on farms is another, more recent, technique of increasing productivity by using less labor. Naturally, as labor costs fall due to the economy using more and more natural resources, economic growth is stimulated, resulting in a further increase in the overall use of raw materials and fossil fuels. In other words, a positive feedback mechanism is operative. Note that this growth mechanism must falter and eventually fail since fossil fuels will eventually become scarce and prices of materials and energy derived from them will start rising.

The other key element of the EGF is innovation and the creation of new commodities and products, some from the fossil fuels themselves, and some from other material resources. Coal itself became a commodity to compete with, and eventually replace, charcoal. Coke and coke oven gas followed as commodities. Electric power is now a commodity. The same kind of thing happened later when petroleum was exploited at first to provide an alternative to whale oil for illumination purposes (oil lamps). Gasoline was a refinery by-product, used only as a cleaning agent at first. Of course, heating oil, diesel fuel, lubricants, petrochemicals, plastics, synthetic fibers, and numerous other products were developed over time to exploit the raw material more fully. The development of internal combustion engines and self-propelled vehicles has followed the availability of low-price fossil fuel energy.

It is important to emphasize that the feedback cycle is not merely a particular form of learning-by-doing, nor is it fundamentally attributable to scale economies, although both learning and scale are obviously involved and can reinforce it. One of the two key elements of the cycle is the availability, at ever-lower costs, of fossil fuels, initially coal, and subsequently petroleum and natural gas or nuclear energy. These are, of course, material resources. But they differ from other resources, such as construction materials, in that they are not embodied in products (except for plastics and synthetic fibers). They are entirely consumed for the purpose of generating heat, mechanical power or (a slight generalization) electric power.

A growth theory that includes the EGF cycle can address several new questions: To what extent was past economic growth dependent on the exploitation of this form of capital? To what extent is current and future growth still dependent, directly or indirectly, on fossil fuels? Is there another possible feedback cycle "growth engine" that could replace it in the future?

*2. The Salter cycle growth engine*

A second mechanism for driving economic growth by reducing costs became increasingly important in the 19th century. Scale economies, standardization, division of labor by specialization and 'learning by doing' were important in all kinds of manufacturing. Once again, cost reduction encouraged demand growth and vice versa. This has been called the "Salter cycle", indicated by loop 2 in *Figure 1*.[2] Of course, growing demand for manufactured products implies increased consumption of raw materials of all kinds. It is important to emphasize that the scale-learning mechanism, by itself, is unable to generate perpetual exponential growth at a constant rate. The reason is that costs decline in relation to output at a declining rate, and demand increases in relation to prices at a declining rate. To maintain a constant rate of growth, therefore, it is necessary to postulate a product mix that changes and evolves (becoming more complex, for instance) with a continuously increasing price elasticity. Up till now businesses have been quite successful in fostering such a process via product innovation and marketing (shape, fashion, packaging, etc.). We return to this point shortly.

It would seem that economic growth in the industrial countries, at least until recently, has been driven primarily by a combination of these two feedback mechanisms. What does this approach then say about the relationship between environment, resources and growth? Economic *activity* is very materials intensive at present, which is partly related to the fact that economic *growth* has been very tightly linked to natural resource extraction and use. However, neither the resource-driven growth nor the scale-driven mechanism is sustainable for the indefinite future. This is partly because the natural resources themselves are bound to become scarcer (and more costly) and partly because the resulting pollution is becoming increasingly intolerable.

3. *The value creation or 'dematerialisation' growth engine*

Loop 3 in *Figure 1* represents a third growth mechanism essential to permit sustainable future economic growth. Resource productivity and labor-productivity must increase simultaneously, not by increasing labor productivity at the expense of consuming ever more natural resources. The mechanism for achieving this result can only be to add value to, and extend the useful life of durable products while simultaneously reducing use of fossil fuels and other dissipative intermediates. This strategy can be characterized as "dematerialization"; it also includes reuse, renovation, re-manufacturing and recycling on various levels. This is tantamount to substituting man-made "useful" information for natural resources [Ayres & Miller 1980; Ayres 1987, 1994]. Macro-level dematerialization may result from lighter products, miniaturization and new technologies (computers and information technology), and sectoral shifts to services. The latter may go along with demographic and life-style changes. Through these processes, the economy will automatically focus on the production of final services rather than material. It will then be natural for managers to develop means for delivering services with the minimum possible requirement for material and energy inputs.

Of course, increased useful life-time, by means of repair, renovation and re-manufacturing, will necessarily sacrifice some of the advantages of mass production. These activities are inherently more labor intensive than capital intensive, which may seem, at first, like a disadvantage from the perspective of labor productivity. But, if more labor is needed for each machine or other material product in service, where is the macroeconomic gain? Part of the answer is that repair, renovation and re-manufacturing not only reduce the losses of primary extractive raw materials but also reduce the loss of value previously added to materials by prior production processes. In other words, the dematerialization and recycling mechanism sharply reduces the rate of depreciation of durable goods and physical capital. This is a real macroeconomic benefit, because depreciation means a significant loss (or cost) to the economy.

But cutting back depreciation does not *ipso facto* generate new demand. The second part of the answer, therefore, must lie elsewhere. Whereas the Salter cycle growth mechanism depends on price reductions (due to economies of scale) to generate new demand, the third cycle must generate new demand in some other way. The obvious (and probably only) mechanism for doing so is via accelerated technological innovation in the service sectors, as illustrated schematically by loop 3 in *Figure 1.* This mechanism is very similar to the one that Romer (1986) has proposed, except that there is no need for new knowledge to be public. Spillovers can and usually do occur at the product level, e.g. lasers have facilitated unexpected applications in eye surgery, printers, CDs and a host of other sectors. We are now seeing this cyclic process operate in the domain of information technology (IT). We may see it soon in bio-technology. It may thus affect both recycling/reuse and dematerialization.

Ideally, one might think that a complete growth model should reflect each of the three feedback effects explicitly, and independently of the others. However this is easier said than done. For instance, during the early phases of the industrial revolution there was a very strong interaction between economies of scale and learning in the manufacturing sector and the cost of energy/power, and similarly for the cost of metals (iron and steel) and machinery. This generated a new technology (railroads and steamships) which cut costs of transport dramatically and promoted trade. There was virtually no R&D in the modern sense, until the last third of the 19th century (e.g. Edison). Before that, R&D was indistinguishable from the cost of capital equipment, and essentially all of what we would call R&D went into improving production processes. Resources were not devoted to consumer product development until the last two decades of the 19th century, beginning with the telephone, bicycle, automobile and a variety of household and kitchen appliances. The point is that some of the most important feedbacks of the early industrial revolution may no longer be quantitatively significant. because of structural change. Yet a simple single-sector model must allow for all possible feedbacks but cannot distinguish between the sector-specific mechanisms.

In subsequent sections a formal growth model is presented that incorporates all three growth mechanisms. In order to develop this model completely an important building block is needed, namely a production function that provides a link between physical and value units.

## 4. The production function

In order to formulate a general production function suitable for our purpose of implementing the three growth mechanisms of the previous section two dimensions need to be explicitly considered: the material or physical dimension of production; and its value dimension.

Extractive physical resources are needed, either for the production process, or to be embodied in the product, or both. The mass balance condition (first law of thermodynamics) must hold, of course. Some fraction of these physical resource inputs is either discarded at the outset or converted into dissipative intermediate products that are utilized (and lost) in the production process. The remainder is embodied in “finished” goods that compose the composite physical output. The latter is also eventually lost, when the good is depreciated or ‘used up’ and discarded, except to the extent that it is recycled.[3]

Hereafter, both resource inputs (*R*) and waste outputs (*W*) from the economy are defined and measured in terms of mass or exergy flows. Exergy is an unfamiliar concept to most economists, but it is more appropriate (and accurate) than either mass or energy, since it is applicable to both fuels and non-fuel resources.[4] Of course, *R* also has a positive price or monetary value, while *W* may, in principle, be assigned a negative price and negative monetary value.[5] However these values are irrelevant to the following discussion.

Using the mass-balance condition it is now possible to introduce two different, but complementary, measures of technological progress (see also Ayres 1978; van den Bergh 1999). The first of them relates to a measure of the technical efficiency of the production process, namely the ratio of resource (e.g. mass or exergy) inputs embodied in the physical output (finished products) to the gross mass of material extracted from the environment. The difference between input and output is lost as process waste *W*, which incidentally is harmful to the environment. The technical efficiency of production *f* can be characterized as follows:

$$f = \frac{R-W}{R} = 1 - \frac{W}{R} \tag{4}$$

Note that *f* is a fraction (i.e. a dimensionless number), necessarily limited to the range of values $0 < f < 1$, assuming that $0 < W < R$, i.e. there is always some waste and the amount of waste is bounded from above by the amount of resource input (measured in the same units). Evidently a combination of simple learning (experience), plus scale economies and new knowledge generated by R&D can account for increasing efficiency *f* of the production process in terms of the use of material (exergy) resources. A general formulation of *f* is therefore $f(K,U,N)$, with the arguments denoting capital, knowledge (human capital) and experience (cumulative production), respectively. The more efficient the process, the less waste. Hence there is a direct relationship between technical efficiency *f* and product cost *C*, which would suggest something like $1/C = f(K,U,N)$. This point will be taken up in Section 6.

The second new measure is the monetary value of the output of the economy per unit mass of finished material goods produced, i.e.

$$g = \frac{Y}{R-W} = \frac{Y}{f\,R} \tag{5}$$

The conceptual difference between the two measures is important, although there is clearly a relationship between them. First, g (unlike *f*) is not a dimensionless number; it is measured in \$/mass or \$/exergy) and can take any nonnegative value. Second, the inverse of *g* is a measure of the phenomenon now commonly known as 'dematerialization' [Herman *et al.* 1990; Cleveland & Ruth 1997; Ayres *et al.* 2000]. Therefore, *f* can be referred to as the efficiency measure and *g* as the dematerialization measure.

The above relationship can be expressed as a production function, namely of the form

$$Y = f\,g\,R \tag{6}$$

where $Y = Y(U,K,R)$ if $f = f(U,K,R)$ and $g = g(U,K,R)$. This automatically satisfies the Euler condition of constant returns to scale at the macro-level if (and only if) *f* and *g* are homogeneous functions of order zero. This condition is satisfied, for instance, provided the functions *f*, *g* depend only on ratios of other factors of production. For instance, we might try

$$f = f\,(K^{a}U^{1-a}/R) \tag{7}$$

and

$$g = g\,(K^{b}U^{1-b}/R) \tag{8}$$

Here f'>0, g'(0)<0 and g">0. The final choice of functional forms for *f* and *g* must obviously depend on the use of other economic knowledge

A very helpful empirical relationship that can be used at this point to help in the selection process is the so-called *E/y* (environmental or energy Kuznets) curve, with *E* some indicator of energy use or environmental pressure and *y* = income/capita (GDP/Capita). In our notation we can write

$$E/y = (E/Y)Pop = Pop/fg \tag{9}$$

with *Pop* denoting the population size. For some indicators *E* the ratio *E/y* has for most developed countries and over a certain income range the form of an 'inverted U' or bell shape. The efficiency measure *f* can be estimated numerically. In fact, this has been done, for the USA, for the period 1800-2000 (see Ayres 1999). While the estimation procedure was necessarily crude and the data are not very precise, there can be little doubt that *f* is a monotonically increasing function. This is also in accordance with engineering intuition. Therefore, *g* must display a 'U-shape'. What this implies is that during an earlier period of economic development (characterized as the "cowboy economy" in an earlier paper by one of us [Ayres 1998]) the value of service outputs of the economy was actually declining in relation to the material output (and extractive resource input), whereas in the past half-century it has been increasing.

The function *f* increases monotonically, but the functional relationship between *f* and *K* cannot be linear. On the contrary, as *K* becomes larger and larger, *f* approaches its upper limit of unity more and more slowly. Since *fg* has a 'U-shape' *g* cannot be a simple function of (increasing) *U* or *U/R*. We can now choose functional specifications that are consistent with these patterns: For instance

$$f = 1 - \exp[-\boldsymbol{l}\,(K^{a}U^{1-a}/R) \tag{10}$$

$$g = A\,(R/(K^{b}U^{1-b}))^{h_1} + (1-A)(K^{b}U^{1-b}/R)^{h_2} \tag{11}$$

It can be shown that *g* in equation (11) has a minimum when

$$(R/(K^{b}U^{1-b}))^{h_1+h_2} = ((1-A)/A)\boldsymbol{h}_2/\boldsymbol{h}_1 \tag{12}$$

$$\dot{K} = I - \delta K \tag{13}$$

$U$ — should increase the value or quality of the product and thus the value of economic output per unit of mass, i.e. $g$. The equation might take a form such as

$$\dot{U} = J + \varepsilon U \tag{14}$$

where $J$ is the investment in new knowledge, and $\varepsilon$ a parameter quantifying intertemporal information spillover. This is related to static technology or knowledge spillover from more advanced regions or sectors to less advanced counterparts. This parameter reflects the stylized fact that, as the stock of scientific and technological knowledge grows, it is easier to create more knowledge. Such an assumption is fundamental to the so-called ‘new’ endogenous growth theory and it is consistent with real-world experience.[7]

Aggregate savings $S$ is now the sum of the two investment flows.

$$S = I + J = s\,Y \tag{15}$$

To incorporate new knowledge in a product, of course, involves coincidental investment in production processes and equipment. Thus, while process R&D can occur without product R&D, the converse makes no sense. In other words, it is *not* possible to achieve perpetual economic growth in the real world by investing only in pure knowledge. There must also be an essential material component of the system. This is contrary to the way investments are generally regarded in standard endogenous growth models. In other words, new knowledge is partly embodied in physical capital. This can be represented by a definite relationship between investment in new knowledge and investment in physical capital, such as $I = h\,(J)$. The simplest form of the relationship would be a linear one, viz.

$$I = g\ J \tag{16}$$

where $g$ is a constant that would have to be determined empirically. This says that the investment necessary to assure perpetual growth by producing improved goods or services is simply proportional to the investment in R&D. Then we get

$$S = (\,1 + g\,)\,J = s\,Y \tag{17}$$

## 6. Formalizing the demand feedback mechanism

We now propose an extension of the model that incorporates both a scale and learning mechanism on the production side and a price elasticity of demand mechanism on the demand side. This might be based on the Salter cycle discussed in Section 3. To begin with, we assume that output consists of a composite good, with value $Y$, produced at a cost C and a price $P$. We also introduce a composite price elasticity of demand $\sigma$ and a composite cost reduction (learning) parameter $b$. It is important to emphasize that the price $P$ is not the same as the consumer price index, (which reflects inflation). It must be interpreted as the "real" price of our composite good, holding service value constant. In a single-sector economy consisting of many small competing producers of identical products or commodities, the price $P$ and the cost $C$ can be assumed to be identical or proportional (the cost of distribution being lumped with production cost).[8]

Hence in the simplest case, technical change is restricted to the cost of production and demand is a function of price (equals cost) alone. Growth results from the cyclic feedback between falling prices and increasing demand (equated to output). The generalized Salter cycle model of growth can now be formulated in terms of the two independent parameters. Price elasticity of demand $\sigma$ is usually defined (as a positive number) as follows:

$$\sigma = -\frac{P}{Y}\frac{\partial Y}{\partial P} \qquad (18)$$

whence

$$\frac{\partial \ln Y}{\partial t} = -\sigma\left(\frac{\partial \ln P}{\partial t}\right) \qquad (19)$$

Note that the price elasticity σ need not be a constant, though it is usually assumed to be. In fact, as will be seen shortly, it *cannot* be a constant in the case of a constant rate of exponential growth.

In the absence of R&D the price elasticity of the composite good can be interpreted as a time preference, as the consumer can choose between consumption now or investing and having more consumption in the future. In a more complex case with two types of investments ($I$ and $J$), in productive capacity and R&D, the price elasticity reflects the choice between current consumption and investment either to increase future consumption or to improve the quality of the good. The latter is related to the fact that composite product quality increases depend upon new knowledge through R&D. Since the dematerialization measure $g$ is a measure of quality improvement by definition it follows that $g$ must be a function of U.

It is reasonable even in a multi-sector economy to assume that the market price of the composite good $P$ is a constant proportion of the cost of production $C$. This might be interpreted as a cost mark-up pricing relationship

$$P = mC \qquad (20)$$

with $m$   1.

Modelling of the cost $C$ follows the familiar experience or learning curve as applied to the case of the composite product, viz.

$$C = (c + N)^{-b} \qquad (21)$$

Here $b$ is usually an empirically determined parameter, in the range between zero and unity, characteristic of the product or industry, as shown in *Figure 2*.[9] It is a measure of the rate of cost reduction as a function of cumulative production experience; the larger $b$, the faster costs fall as experience increases. However, in our case it is assumed to apply to the whole economy (i.e. the composite good) and there is no inherent bar to allowing $b$ also to be a function of time, hence a variable. Again, although $b$ is usually taken to be a constant, this assumption can also be relaxed. Experience $N(t)$ is given by

$$N = \int_0^t Y(x)\,dx \qquad (22)$$

[ Insert *Figure 2. Parameters of the experience curve in various industries* ($b$= -ln(1-$a$)/ln2 with $a$ experience parameter). ]

## 7. Analytical results

It is interesting to investigate the conditions (if any) under which the output of the single sector Salter cycle economy $Y$ grows exponentially at a constant rate $r$, viz.

$$Y = Y_0 \, \mathrm{e}^{r\,t} \tag{23}$$

This approach can be motivated by realizing that a constant growth rate is something that most governments seem to strive for. It follows by direct integration over time that

$$N = \frac{Y_0}{r}\left(\mathrm{e}^{r\,t} - 1\right) = \frac{Y - Y_0}{r} \tag{24}$$

Substituting (24) in (21) yields

$$\ln\ C = -\,b\,\ln\left(\ c + \frac{Y - Y_0}{r}\right) \tag{25}$$

Together with (19) and solving for $s$ we get

$$\frac{1}{s} = -\,b\left(\frac{r\,Y}{c\,r + Y - Y_0}\right) - \frac{\dot{b}}{r}\ \ln\left(\ c + \frac{Y - Y_0}{r}\right) \tag{26}$$

where $\dot{b} = \dfrac{d\,b}{d\,t}$.

Now check the two limiting cases, $t = 0$ and $t \to \infty$. At time $t = 0$ $Y = Y_0$ and one obtains

$$\frac{1}{s} = -\frac{b}{c}\,Y_0 - \frac{\dot{b}}{r}\ \ln c \tag{27}$$

which is well-behaved for reasonable combinations of parameters, recalling that $0 < b(\ t\ ) < 1$. The initial value of σ (at time $t = 0$) is determined by $c$ and the initial value of $b$ (at $t = 0$), plus one other parameter. The other limiting case, as $t \to \infty$ leads to another simple differential equation for $b$, viz.

$$\frac{1}{s} = -\,r\,b - \dot{b}\,t \tag{28}$$

For this expression to remain non-negative it is evident that, for very large $t$, the experience parameter $b$ cannot be decreasing. The product $\dot{b}t$ must therefore vanish identically or approach a constant value from below for large $t$.

Evidently there are many functional forms for $b$ that will satisfy this requirement. The simplest is probably the familiar logistic curve, which is the solution of the differential equation

$$\dot{b} = k\left(1 - b\right)b,\ b > 1 \tag{29}$$

where $k$ is a constant. The general solution of (17) is

$$b = \frac{e^{kt}}{\left(\frac{1}{b_0} - 1\right) + e^{kt}} \tag{30}$$

where $b_0 = b(0)$. For large values of $kt$ we see that $b \to 1$, while the product $\dot{b}t$ approaches zero. In the limit of very large $t$, the price elasticity of the composite product $s$ approaches unity monotonically from above.

The foregoing shows that for a model economy with a Salter cycle demand feedback mechanism in place, perpetual exponential growth at a constant rate $r$ is possible but the price elasticity $\sigma$ cannot be constant. In fact, the price elasticity in such an economy must decline monotonically. In effect, the composite output becomes less 'luxury-like' and more 'commodity-like' over time. This is, of course, consistent with the usual experience for any given product, so it could arguably be true for the composite product.

More surprisingly, perhaps, the composite experience parameter $b$ cannot be constant either. It, too, is a variable that must increase monotonically over time. Again, to maintain a constant rate of economic growth, the *rate* of cost reduction (e.g. due to learning) per unit of increasing cumulative production must increase monotonically. This might be justified by the notion that $b$ is somehow a proxy for the knowledge-content of the production process, and that the greater the stock of knowledge, the faster new knowledge can be generated and utilized.

With this interpretation, the Salter cycle model is qualitatively consistent with some of the recent endogenous growth literature models, at least to the extent that they assume that, as knowledge capital increases, the rate of creation of new knowledge also increases. Evidently, the non-constancy of $\sigma$ and $b$ means that perpetual exponential growth is *not* consistent with an unchanging composite product (or mix), although we started with that assumption. On the contrary, the product mix must evidently be changing irreversibly over time.

Next, one would like to know what resource input level is needed to maintain a constant growth rate. Solving the system of equations (6), (7), (8), (13), (14) and (23) yields

$$dR/dt = \frac{rfgR - (f'g + fg')(\alpha K^{a-1}U^{1-a}\dot{K} + (1-\alpha)K^{a}U^{-a}\dot{U})}{fg - (f'g + fg')K^{a}U^{1-a}/R} \tag{31}$$

The terms with $\dot{K}$ and $\dot{U}$ represent the effects of a changes in capital and knowledge on production that need to be compensated ('-' sign) by a change in $R$ such that the growth rate remains constant. *dR/dt* <0 reflects absolute dematerialization, and *d(R/Y)/dt*<0 relative dematerialization. The latter implies that $\dot{R}/R < \dot{Y}/Y$. The result in (31) provides the basis for numerical results presented in the following section.

## 8. Numerical results

The features of the growth model presented in sections 4 to 6 will be further studied by numerical simulation, for two reasons. First, the model with the three feedback mechanisms is too complex for obtaining explicit analytical solutions. Second, we are not interested very much in dynamic optimization with the model, as this seems an artifact. Instead, we aim to examine how the model system behaves under different constant rates of growth. *Appendix A* lists the model equations, reflecting functional specifications and parameter values. Approximate constancy of growth rates is arranged by adding equation (31) to the model specified in sections 4 to 6.

The results under the condition that the growth rate is constant are shown in figures 3 to 13. The following variables are shown. *Rsust* is the level of resource input that would be needed to realize a constant growth rate given values of all other relevant variables, notably *U* and *K*. *Rsust* is the result of applying the change in resource use (*R*) as given by (31) to *R*. The variable *Y* denotes production or income (indicative of income per capita given the constant population size). *f* and *g* denote the functional values in (10) and (11), or the technical efficiency and dematerialization measures, respectively. *P* is the price of the composite good.

*Figure 3* shows results for a constant growth rate equal to 1 %. *Y* increases due to the interaction impact of capital (*K*) accumulation and knowledge (*U*) accumulation on *f* and *g*, and changes in resource input (*R* or *Rsust*). Resource input requirements are decreasing over time. Initially, the efficiency component of production (*f*) is positive and increasing while the dematerialization component (*g*) is negative and increasing. Later on, the increases in efficiency is slower (digressively) than its dematerialization component (progressively). Finally the price of the composite good falls due to the fact that production (and indirectly its growth) leads to experience, which reduces the cost of production, as can be seen from equation (21). *Figure 4* summarizes the results by plotting resource requirement against income under the assumption of constant growth at the rate 1 % p.a. When growth is this slow, the economy is capable of reducing its need for resources.

*Figure 5* shows results for a constant growth rate equal to 1.5 % p.a. Dematerialization (*g*) and efficiency improvements (*f*) are inconsistent with such a high rate of growth until some capital accumulation has occurred, shown by an initially increasing level of *Rsust*. After some time, however, resource input can fall while maintaining the growth rate constant, due to improvements in technical efficiency induced by accumulated capital, and ultimately also in dematerialization. This is an example of the environmental Kuznets or inverted-U curve for material resource use (and indirectly resource extraction as well as emission of pollutants related to this resource), shown in *Figure 6*. This pattern can be regarded a sort of middle case, resulting for constant growth rates in the range of 1.1 % to 1.9 %. Patterns for $f$ and $g$ are similar to those under the growth rate of 1 %.

*Figure 7* shows the results for a growth rate equal to 2 %, which is so high that required resource input (*Rsust*) increases over the entire simulation period, although slightly digressively. In other words, $K$ and $U$ accumulation are insufficient for realizing a 2 % constant growth rate through efficiency improvements and dematerialization. Dematerialization begins about halfway through the simulated time period. The environmental Kuznets curve is no longer observed, and instead resource inputs increase (digressively) with income, shown in *Figure 8*. This qualitative result is also found for higher growth rates. *Figure 9* show the results for a growth rate equal to 3 %. In this case required resource inputs increase progressively and dematerialization is never realized. *Figure 10* shows that at this high growth rate required resource inputs rise almost linearly with income. This is due to the combined effect of changes in $K$, $U$ and $R$ (or *Rsust*).

The qualitative patterns for $f$ and $g$ change again, beyond a constant growth rate of about 5 % and 6 %. *Figure 11* shows results for a growth rate equal to 5.2 %. Here the efficiency curve is U-shaped, and the dematerialization curve inverted-U shaped. *Figure 12* shows the patterns for a 6 % constant growth rate. Here efficiency is decreasing and dematerialization increasing. For higher growth rates the qualitative nature of the patterns for all variables remains the same. *Figure 13* shows the results for a growth rate equal to 50 %, which can be regarded as a sort of limiting case, where ultimately technical efficiency is minimal, dematerialization is maximal, and the growth patterns of income or production and required resource input coincide. The minimal efficiency means that almost all resource input results in waste, consistent with the linear relationship between income changes and resource requirements at a very high rate of growth.

The numerical findings show that the qualitative patterns change dramatically as the constant growth rate is increased. Three patterns show remarkable shifts. First, the relation between required resource input given a constant growth rate and income goes through three phases: decreasing, inverted-U, and increasing. Second, the efficiency curve ($f$) goes through three phases: increasing, U-shaped, and decreasing. Third, the dematerialization curve ($g$) goes through four phases: U-shaped, decreasing, inverted-U shaped, and increasing. These findings and the associated growth rate ranges are summarized in *Table 1*. They imply that the synergetic impact of changes in capital, knowledge and resource use are not easily predictable.

*Table 1. Summary of patterns.*

| Growth rate (%) | Relation between required resource use under a constant growth rate (*Rsust*) and income ($Y$) | Efficiency curve ($f$) | Dematerialization ($g$) curve |
|---|---|---|---|
| 1 | Decreasing | Increasing | U-shaped |
| 1.1 – 1.9 | Inverted-U | Idem | Idem |

| | | | |
|---|---|---|---|
| 2 | Increasing (digressively) | Idem | Idem |
| 3 | Increasing (almost linearly) | Idem | Decreasing |
| 5.2 | Idem | U-shaped | Inverted-U shaped |
| 6 and higher | Idem | Decreasing | Increasing |

Although the functional specifications and parameter values are not based on empirical data, one can expect these patterns to result over a sufficiently wide range of (constant) growth rates. Of course, the main subsequent question is at which growth rates qualitative changes in patterns will occur. This can only be answered with an empirical study. The model presented here provides a disaggregated framework for tackling this question, as well as for clarifying the underlying efficiency increasing and dematerialization mechanisms.

[ Insert *Figures 3 to 13* ].

## 9. Conclusions

Economic growth *must* be accompanied by structural change, which implies continuous introduction of new products and new production technologies, and changes in efficiency and dematerialization. Section 3 proposed a more disaggregated view on growth engines or mechanisms. The simple single-sector single-product model of national income allocation based on factor productivities that has historically been used to select and justify the choice of constant output elasticities for a Cobb-Douglas type of production function is not applicable to the case of a growing economy. Instead, an alternative production function was proposed in section 4. Finally, a demand feedback mechanism was based on the Salter cycle, which combines the effects of scale, learning and price elasticity changes.

Analytical results indicate that given the Salter cycle mechanism perpetual exponential growth at a constant rate is possible but only for a declining price elasticity of the composite product. This means that the composite output becomes less ‘luxury-like’ and more ‘commodity-like’ over time. In other words, perpetual exponential growth cannot occur with an unchanging composite product. It is worth pointing out here that the imputed behavior of $\sigma$ and $b$ in the Salter cycle model is entirely consistent with the ‘life-cycle’ interpretation of technological innovation and progress [e.g. Nelson 1962; Ayres 1984, chapter 3]. In brief, when an innovative new product or service is introduced it stimulates a competition among followers and imitators to find the best technical solution. During this stage (‘infancy and childhood’) competition in the marketplace is basically on performance, and R&D can be characterized as performance-enhancing. However, there is a period in every such free-for-all when one or a few competitors emerge from the pack and become dominant. Thereafter, the product design stabilizes (although incremental improvements continue) and the basis of market competition shifts from performance to price. Standardization of design permits optimization and mechanization of the production process to minimize costs. Thus R&D during this stage (‘adolescence and maturity’) becomes focussed on production technology. This is where capital and energy are systematically substituted for labor, and economies of scale are critical. The mature phase, of course, is characterized by standardization (i.e. ‘commoditization’) of the product and decreasing numbers of competitors. In other words, competitors begin to merge and form themselves into an oligopoly. The logic of this tendency — which is very clearly observable today — is that profits will otherwise fall to zero in a fully competitive market with a standardized commodity product.

Further model analysis was based on numerical simulation. For this purpose the model was extended with an equation that calculates the (change in) resource input level required for maintaining a constant growth rate. The results show that qualitative patterns change when the (constant) growth rate is increased. In particular, three patterns show interesting shifts in qualitative structure: the relation between required resource input given a constant growth rate and income, the efficiency curve, and the dematerialization curve. While environmental Kuznets curves seems possible for relatively low growth rates, they are no longer found for growth rates above a certain minimum level. For sufficiently high growth rates required resource input increases almost linearly with income. Moreover, the rate of growth influences the type of patterns found for technical efficiency and dematerialization. These patterns follow from the combined impact of changes in capital, the stock of knowledge and resource use. No simple relation between these exists, implying that prediction of patterns is not straightforward. The reason is that the three growth mechanisms – relating to resource use, demand-cost feedback and value creation or dematerialization – provide for interactions that defy any simple generalization on a macro level. This means that theoretical results provide insufficient information to say anything about future patterns of growth in relation to resource use. Empirical information, among others, on growth rates and initial conditions needs to be added to decide which growth/resource-use regime is most relevant.

The main weakness of the standard production function as used in existing growth models is that it does not provide sufficient information about what is actually happening when substitution takes place, for instance, from materials use to capital use in production. This is problematic from the viewpoint of both interpretation and prediction. The model proposed here proposed a different production function specification that aims at clarifying the relationship between the physical and value dimensions of economic growth. The overall model offers a starting point for more informative empirical research, putting such research as testing the environmental Kuznets curve hypothesis in a theoretical context. Such a context has up till now been lacking (see de Bruyn and Heintz 1999).

From an empirical perspective, the remaining problem is to quantify the two macro-variables $f$, $g$ and trace their historical trends. From an economic policy perspective, the problem is to control and manage them to achieve long-term sustainability. In view of the discussion above, the most relevant policy tool is R&D investment, supplemented by regulation as applied to natural resource utilization, especially energy use efficiency and 'dematerialization', where the latter would cover recycling of materials and products.

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# Appendix A. Numerical Model Equations [10]

```
Aux1(t) = Aux1(t - dt) + (Yt - Ytmin1) * dt
INIT Aux1 = 62
{value of Y on t=-1}
Yt = Y
Ytmin1 = Aux1
Aux2(t) = Aux2(t - dt) + (Pt - Ptmin1) * dt
INIT Aux2 = 1.1
{value of P on t=-1}
Pt = P
Ptmin1 = Aux2
K(t) = K(t - dt) + (I - deprec) * dt
INIT K = 100
I = coef*Y
deprec = delta*K
N(t) = N(t - dt) + (dN) * dt
INIT N = 0
dN = Y
Rsust(t) = Rsust(t - dt) + (dRplus - dRmin) * dt
INIT Rsust = 100
dRplus = MAX(dR,0)
dRmin = MAX(-dR,0)
U(t) = U(t - dt) + (dU) * dt
INIT U = 100
dU = J+epsilon*U
A = 0.7
alpha = 0.5
b = 0.1
beta = 0.5
c = 30
coef = s/(1+gamma)
const_growth_rate = 0.00
Cost = EXP(-b*LOGN(c+N))
delta = 0.05
dP = Pt-Ptmin1
dR = (const_growth_rate*f*g*Rsust-(f'*g+f*g')*(alpha*K^(alpha-1)*U^(1-alpha)
*(I-deprec)+(1-alpha)*K^alpha*U^(-alpha)*dU))/(f*g-(f'*g+f*g') *K^alpha*U^(1-
alpha)/Rsust)
dY = Yt-Ytmin1
epsilon = 0.02
eta1 = 1
eta2 = 1
f = 1-EXP( -lambda*K^alpha*U^(1-alpha)/R )
f' = lambda*(1-f)
g = A*( R/(K^beta*U^(1-beta)) )^eta1 + (1-A)*( K^beta*U^(1-beta)/R )^eta2
g' = -A*eta1*(Rsust/(K^beta*U^(1-beta)))^(eta1+1) + (1-A)*eta2*(K^beta*U^(1-
beta)/Rsust)^(eta2-1)
{Derivative of g}
gamma = 0.5
growth_rate = dY/Ytmin1
J = gamma*I
lambda = 1
m = 1.2
P = m*Cost
R = w1*100 +w2*Rsust
```

```
{weights w1 and w2; w1=1 and w2=0 means constant resource input; w1=0 and w2=1
means constant growth rate}
s = 0.2
sigma = (dY*Ptmin1)/(Ytmin1*dP)
Y = f*g*R
```

# Endnotes

[1] An entirely different type of study addressing the relationship between resource availability and growth rates is Rodriguez and Sachs (1999). They show that given Ramsey type of optimal growth, resource abundant economies will overshoot the steady state equilibrium, followed by a convergence to this steady state, thus implying negative growth rates. This is regarded as an explanation of the empirical observation that some resource-abundant economies, mainly developing countries, grow relatively slowly. The type of model used is very traditional, and far removed from the approach presented here.

[2] The cycle is named for an English economist, W.E.G. Salter, who wrote a very perceptive book on growth and technological change (Salter 1966).

[3] We use the term is its most general sense, to include repair, renovation and remanufacturing, as well as recovery of wastes as raw materials.

[4] The term ‘energy’ is not used correctly in most economic studies. For the sake of conceptual precision ‘energy’ should be replaced by the word ‘exergy’, which refers to that part of the energy flux that is available to do useful work and, which can be used up in an economic process as work is done and energy becomes less available. The important difference between energy and exergy is that exergy is not a conserved quantity. Exergy is measurable given an environmental medium reference state with which it must ultimately reach thermodynamic equilibrium (usually the atmosphere, ocean or earth's crust). For convenience, exergy content can be equated to the electric power output. Moreover, exergy is definable and measurable for all materials, not just fuels. Since the exergy measure is applicable to and computable for all materials, as well as all forms of energy, it can be used for purposes of aggregation in situations where the monetary measure is inappropriate or inadequate. This approach to resource accounting has been proposed, in particular, by Wall (1977, 1986, 1990). By the same token, the aggregate output of useful products, as well as the generation of material wastes, can also be expressed, separately, in exergy terms (Ayres *et al*. 1998).

[5] This statement does not imply any theory of value. It merely means what it says, that materials can be characterized by mass, and mass flows can be measured quite independently of their monetary value.

[6] As it happens, a simple two-parameter functional form that does fit the actual economic data very well for three major countries (US, Germany, Japan) has been derived on the basis of thermodynamic arguments (Kümmel *et al* 1985, 1998). The form these authors have selected, using the author's notation for the two fitting parameters, can be written as follows:

$$f\ g = e^{a_0\left[\left(1-\frac{L}{K}\right)+\left(1-\frac{R}{K}\right)-c_1\left(1-\frac{L}{R}\right)\right]}$$

However, it is important to point out that this functional form is *not* consistent with long term growth, given the three asymptotic conditions specified above, namely $\frac{L}{K} \to 0$, $\frac{R}{L} \to 0$ and $\frac{R}{K} \to 0$. In other words, the functional form that best fits recent growth patterns implies that economic growth will cease if extractive resource consumption does not continue to increase.

[7] In fact, the idea that knowledge breeds knowledge is an old one in economics. See, for example, Ayres (1944, Chapter VI p. 144) and earlier references cited there.

[8] It must be acknowledged, however, that this assumption is crude, given the fact that most investment in new capacity is actually financed by profits, not household savings. Profits are the difference between prices and costs. Also, it must be acknowledged that profits depend very much on competitive

conditions, i.e. market structure. In the idealized world of small, competitive price-taking firms profits would be impossible and investment by firms would not occur.

[9] The more familiar 'experience' parameter (usually denoted by the letter a) is the fractional decrease in costs resulting from a doubling of cumulative production experience N. It is easy to show that $b = -\frac{\ln(1-a)}{\ln 2}$. For an extensive discussion of the literature see Cunningham (1980) or Argote & Epple (1990).

[10] The model was programmed in the dynamic simulation package Stella II (Richmond et al. 1987).